arXiv:astro-ph/9612021v1 2 Dec 1996

DISTANT GALAXY CLUSTERS IDENTIFIED FROM OPTICAL BACKGROUND FLUCTUATIONS[1]

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[1] Based on observations made at the W.M. Keck telescope which is operated jointly by the California Institute of Technology and the University of California, and the 60-inch telescope at the Palomar Observatory, California Institute of Technology.

Received ______________________; accepted ______________________

ABSTRACT

We present the first high redshift ($0.3 < z < 1.1$) galaxy clusters found by systematically identifying optical low surface brightness fluctuations in the background sky. Using spectra obtained with the Keck telescope and I-band images from the Palomar 1.5m telescope, we conclude that at least eight of the ten candidates examined are high redshift galaxy clusters. The identification of such clusters from low surface brightness fluctuations provides a complementary alternative to classic selection methods based on overdensities of resolved galaxies, and enables us to search efficiently for rich high redshift clusters over large areas of the sky. The detections described here are the first in a survey that covers a total of nearly 140 sq. degrees of the sky and should yield, if these preliminary results are representative, over 300 such clusters.

1. Introduction

The development of structure in the Universe is one of the principal unanswered questions in cosmology. Although the local structure in the distribution of galaxies is now well delineated (*e.g.,* the CfA survey; Davis *et al.* 1982, de Lapparent, Geller, & Huchra 1986; and the LCRS, Shectman *et al.* 1996), the corresponding distribution of galaxies at large redshifts (z $\gtrsim$ 0.5) is poorly constrained. Clusters are the most recognizable signposts of structure, particularly at high redshifts, but there are relatively few known high redshift clusters. The largest advance of the last decade in the number of known distant clusters comes from the work of Postman *et al.* (1996), who presented a large, well-defined cluster catalog. Their compilation contains 35 clusters with estimated redshifts $\geq$ 0.5, plus 25 clusters from an inhomogeneous sample with estimated redshifts $\geq$ 0.5 (the Postman *et al.* catalog includes clusters identified previously by Gunn, Hoessel, & Oke 1986). Although this is the largest available sample, once one begins to divide the sample on the basis of cluster properties, such as redshift or richness, there are few clusters per bin. To confidently address issues of large-scale structure, and to study cluster and galaxy evolution at high redshift in detail, larger, well-defined samples of distant clusters are essential.

Compiling a significantly larger sample of high redshift clusters using standard identification techniques is difficult because one needs moderately deep, photometrically homogeneous images of a large area of the sky. In previous optical surveys, clusters are identified largely from statistical excesses of resolved individual galaxies on the sky. More sophisticated approaches, such as that by Postman *et al.*, incorporate magnitude and color filters to minimize the contamination from line-of-sight projections. Deep two-color photometry requires the use of a large telescope under photometric conditions and good seeing. The large expenditure of time necessary to do such a project on a 4 to 5-m class telescope makes it difficult to cover very large areas ($\gg$10 sq. degree) of the sky.

An alternative approach to finding distant clusters is described by Dalcanton (1996)

and relies on detecting the light from the unresolved galaxies in a cluster. The success of this technique is predicated on the assumption that the total flux from these distant clusters is dominated by flux from unresolved cluster galaxies. This is undoubtedly true in shallow exposures of high redshift clusters. The light from unresolved clustered galaxies combines to produce a detectable surface brightness fluctuation in relatively shallow, but intrinsically uniform, images of the sky. Once one no longer needs to resolve many galaxies per cluster in order to identify clusters, one can (1) survey a larger section of the sky because the requisite exposure time to detect a particular cluster is shortened and/or (2) use small telescopes, for which it is possible to obtain larger time allocations. Both of these advantages enable one to efficiently survey a large area of the sky. Because the magnitude limit of our survey and that of the Postman *et al.* are roughly similar ($\lesssim 1$ mag difference), we optimistically expect that the surface brightness detection technique will enable us to identify a greater proportion of clusters at $z > 0.5$ than that found by Postman *et al.* (their sample has an average estimated redshift of 0.52 for clusters with estimated redshifts ≥ 0.3). Finally, our method provides an independently selected sample of distant clusters, which is critical for revealing selection biases and determining completeness. The two approaches are complementary.

In this *Letter* we discuss the selection of the first ten candidate clusters from low surface brightness fluctuations in drift scan images and the vetting of those candidates using spectroscopy plus optical imaging. Our results demonstrate that the technique based on surface brightness fluctuations is a viable and efficient way to detect clusters out to beyond $z = 1$.

2. Observations and Data Reductions

We select our initial set of cluster candidates from the drift scan survey ($\sim$ 17.5 sq. degrees) described by Dalcanton *et al.* 1997. Our candidates are 5σ fluctuations over background and typically have some visible signs of substructure, with which we crudely differentiate them from low surface brightness galaxies. Our reduction and analysis procedure includes carefully flatfielding the scans, masking bright stars and galaxies, filtering large fluctuations that are due to sky variations or Galactic cirrus, removing individual resolved stars and galaxies, smoothing the remainder with an exponential kernel of size comparable to the expected core of distant clusters ($\sim$ 5 to 10 arcsec), and identifying the statistically significant fluctuations that are not the result of a low surface brightness galaxy, scattered light, or Galactic dust. We have compiled a preliminary list of 52 such cluster candidates from these images.

We are currently reducing drift scans of another 120 square degrees of sky observed at the Las Campanas Observatory, from which we will identify several hundred such candidates, for our full survey. The results described here are being used to develop more quantitative selection criteria and to train our cluster detection algorithms. Because we are currently conservative in our cluster candidate selection by requiring that the fluctuation also have visible signs of substructure, presumably caused by the few brightest cluster galaxies, we are currently biased toward the lower portion of the accessible redshift range. Therefore, the redshift distribution of the clusters presented here is a conservative estimate of the expected final redshift distribution. This sample is not representative of the final catalog, but demonstrates the viability of the technique. From our current list of candidates, we selected a set of ten that appeared promising.

We have obtained some combination of photometry and spectroscopy of the ten candidate cluster fields and list those observations in Table 1. The V and I-band images were obtained at the Palomar 1.5m telescope during May 9 - 14, 1996. Typical exposures

per object are between 0.5 and 1.5 hours and calibration is done using Landolt (1983, 1992) standard fields. All the fields were observed at least once during photometric conditions. The photometric solutions for the standards show some slight scatter (0.06 mag) that suggests that the nights were not entirely photometric. We propagate this uncertainty, plus the internal uncertainty from the SExtractor (Bertin & Arnouts 1996) photometry, through to the final magnitudes. A listing of the magnitudes will be presented in our study of cluster galaxy properties (Nelson *et al.* 1997).

Spectroscopic observations were done at the Keck telescope using the LRIS spectrograph with a 600 line mm^{-1} grating and a single long slit aperture on Dec 20-21, 1995. The aperture was oriented to include as many individual galaxies as were visible on the guider image (usually 2 to 3 to an estimated $m_r < 22$). The typical exposure time was 30 min. In the end, we obtain a measurable spectrum for 5 to 8 objects per slit position. The images are rectified and calibrated using calibration lamp exposures and the night sky lines (see Kelson *et al.* 1997 for details). Velocities are measured using a cross-correlation technique or centroids of emission lines. The rms redshift difference among redshifts measured from different emission lines in the same spectra is 0.0033 (the typical difference is < 0.0005). In cases where only one emission line is observed, we attribute it to Hβ. There is no ambiguity between Hβ and [O II] because the [O II] line is resolved into the two components at 3726 and 3729Å. The distribution of galaxy velocities in each of the 10 observed fields is shown in Figure 1. We define a clump of at least two galaxies within 1000 km s^{-1} of the clump mean to be a candidate cluster. In Table 1 we list the candidate cluster redshift using the "richest" redshift clump along the line of sight and list the number of galaxies in that clump, N_G. Admittedly, for cases where only two galaxies satisfy the 1000 km s^{-1} criterion, the identification of the redshift pair as indicative of a cluster is suspect (but see below for possible vindication).

3. Discussion

Cluster classification can be enigmatic, even at low redshifts (Zabludoff *et al.* 1993). At higher redshifts, with few redshifts per putative cluster, the task of vetting candidates is even more difficult. To proceed, we adopt 1000 km s^{-1} as a canonical rich cluster velocity dispersion (cf. Zabludoff *et al.*). Each of the line-of-sight redshift distributions for the ten fields contains at least two galaxies within 1000 km s^{-1} of each other at some redshift. Assuming a smooth parent distribution of redshifts defined from the sum of all of our measured redshifts, there is a negligible formal chance of finding two galaxies within 1000 km s^{-1} of each other from among the five to seven observed galaxies in a single field. However, because galaxies are spatially correlated, the probability of finding galaxies clumped in redshift space must be greater that this calculation suggests and must depend on the unknown correlation function at high redshifts.

We conservatively estimate the probability of identifying spurious groups in redshift space directly from our data. By assuming that the four candidate cluster fields in which the richest redshift clump contains only two galaxies are spurious, we infer that the probability of finding a spurious pair in redshift along a random line of sight is at least 0.4 (4 of 10). Adopting this value as the probability of random pairs, we then expect that at least one of these four lines of sight, and at least two of the other six lines of sight, will contain a second random pair. However, only one of the ten fields has a second clump of two galaxies, suggesting that the random probability of pairs is actually less than 0.4 and that at least some of the fields that have a two galaxy redshift clump are probably not spurious cluster detections. A similar argument supports the conclusion that groupings of three or more galaxies are exceedingly unlikely. Therefore, we consider clumps with at least three members to be clusters. We temporarily ignore candidates that consist of a clump of only two galaxies, but we note that at least some are *probably* clusters. We conclude on the basis of the spectroscopy that *at least* six of the ten candidates are *bonafide* clusters.

Photometry can also be used examine cluster candidates. For our nearest cluster candidates ($z < 0.5$), the presence of a cluster is evident from our moderately deep images. However, there are three quantitative photometric signatures of a cluster that might be evident even for the most distant clusters: (1) a spatial clustering of resolved galaxies, (2) a sharp rise in the number counts of galaxies per magnitude at apparent magnitudes fainter than that of the brightest cluster galaxy, and (3) a sharp rise in the number counts per $V - I$ color bin at colors redder than that of a passively evolving, old giant elliptical galaxy.

The radial distribution of galaxies relative to the center of the original surface brightness fluctuation is shown in the lower panel of Figure 2 for the eight candidates for which we have I-band images. In all cases, including the candidates for which only two galaxies were found clumped along the line of sight, the galaxies cluster around the position of the original low surface brightness feature. This confirms that we have identified low surface brightness features produced by a clustered statistical excess of unresolved galaxies on the sky (as opposed to low surface brightness galaxies or fluctuations in the sky emission).

The I-band luminosity functions for galaxies within 40 arcsec of the candidate cluster centers are shown in the upper panel of Figure 2 for the same eight candidates. To crudely quantify the location of the expected sharp rise in the number counts of galaxies if these are indeed clusters, we fit a straight line to the left portion of each histogram. The fit spans the region between the leftmost bin that has at least two galaxies and the peak of the histogram. The magnitude at which the fit intercepts the horizontal axis is referred to as m_I^0. Monte-Carlo simulations with random field centers illustrate that random fields do not produce the signatures seen in Figure 2. First, random fields do not typically show any spatial clustering (only $\sim 20\%$ of the fields showed any central concentration). Second, random fields typically contain few (< 10) galaxies within 40 arcsec and those galaxies are often scattered in magnitude so that one is unable to fit to the bright end of the distribution

in the same manner as for the cluster fields (m_I^0 could be measured in only $\sim$ 30% of the random fields, and the value ranged from 17.6 to over 20). Therefore, both the spatial clustering and the number and luminosities of galaxies in the target fields support the conclusion that the candidates are clusters. The final piece of supporting evidence comes from the correlation between m_I^0 and redshift shown in Figure 3.

The relation between m_I^0 and redshift involves a combination of cosmology and cluster/galaxy evolution. One approach is to calibrate the relationship empirically. We find a strong correlation between m_I^0 and redshift (Spearman correlation coefficient of 0.940 and a 0.9995 probability that this correlation is not a random effect). Excluding the most distant candidate, which appears to lie off the "best" linear relation (our images are insufficiently deep to resolve a significant number of cluster members at $z > 1$), we fit a line with an *rms* redshift scatter of only 0.05. This result further confirms that these eight candidate clusters are real and suggests that m_I^0 may be an excellent empirical cluster redshift indicator over this range of redshifts. A complementary way to determine the $m_I^0 - z$ relation is to assume no cluster or galaxy evolution (*i.e.,* assume that m_I^0 is a standard candle) and simply apply K-corrections and the redshift-distance relation to m_I^0. This approach results in the dashed line in Figure 3 (for $q_0 = 0.2$, $\Lambda = 0$, and K-corrections drawn from Fukugita, Shimasaku, & Ichikawa (1995) for elliptical galaxies). The plotted curve is normalized to the empirical line at $z = 0.3$. The agreement between the empirical and theoretical curves further confirms that the majority of these systems are clusters. Once we obtain a larger cluster sample, we will develop a more sophisticated version of this approach (possibly combined with color information) to photometrically measure redshifts for the majority of the candidates.

Lastly, the V-band data was of insufficient quality to provide unambiguous information on the colors of the cluster galaxies in the more distant cluster candidates, and so we do not discuss it here. The galaxy colors for the nearer clusters are consistent with their spectroscopic redshifts.

4. Summary

We present the initial set of high redshift clusters found by identifying clusters from low surface brightness fluctuations in the background sky (Dalcanton 1996). By analyzing follow-up spectroscopic and photometric observations of ten candidates, we demonstrated that the technique is at least 60%, possibly > 80%, successful, even before we have an adequate training sample in hand to tune our definition of a candidate cluster. These, and future spectroscopically confirmed candidates, will form our classification training sample. If the success rate found here is representative, we expect to identify well over 300 clusters at $0.3 < z \lesssim 1.1$.

The advent of a large sample of clusters with $z > 0.5$ and possibly a significant sample at $z > 1$ opens up detailed cluster and galaxy evolution studies based on carefully constructed samples of clusters, searches for supernovae at z > 1, and searches for X-ray clusters at lower sensitivity levels than those relying solely on X-ray detections. All of these will eventually lead to a better understanding of galaxy and clusters evolution, and cosmology.

Acknowledgments: DZ and AEN gratefully acknowledge funding from the California Space Institute. AEN also acknowledges support from a UCSC Graduate Research Mentorship Fellowship. Financial support for JJD was provided by NASA through Hubble Fellowship grant #2-6649 awarded by the Space Telescope Science Institute, which is operated by the AURA, Inc., for NASA under contract NAS 5-26555. AHG acknowledges support from an NSF Graduate Research Fellowship.

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Figure Captions

Figure 1 - The redshift for every detected galaxy in each of the ten fields is plotted. The order of the fields from top to bottom matches that in Table 1. The filled circles denote galaxies within the 1000 km s^{-1} groupings.

Figure 2 - The I-band luminosity function (top) and radial surface density profiles (bottom) are plotted for the eight cluster candidates (Nos. 1, 2, 3, 4, 6, 7, 8, 9 from left to right) for which we have I-band images. The lines drawn in the upper panel are least-squares fits to the left-hand portion of the histograms from the first bin that has at least 2 galaxies to the peak of the histogram.

Figure 3 - The intercept from Figure 2, m_I^0, is plotted against redshift. The triangles denote candidates with only two galaxies identified in a redshift clump. The solid line is a least-squares fit to the clusters at $z < 1$. The *rms* about this line for $z < 1$ clusters is 0.05. The dotted line represents the expected magnitude-redshift relationship for a $q_0 = 0.2$, $\Lambda = 0$ universe, where the curve has been normalized to coincide with the empirical curve at $z = 0.3$.

Table 1: Cluster Candidates

No.	α			δ			V	I	N_G	z
			(1950.0)				(minutes)			
1	9	12	29.5	47	50	51.0	50	33	3	0.40
2	9	32	50.9	46	34	10.9	80	80	5	0.53
3	10	04	51.3	47	48	05.0	80[a]	83[a]	2	0.73
4	10	07	53.1	47	34	57.1	80[a]	83[a]	3	1.06
5	10	16	22.4	47	35	00.5	- - -	- - -	2	0.41
6	10	38	05.8	46	42	17.5	40[a]	60	2	0.62
7	10	56	44.7	47	53	44.6	50[a]	50	5	0.36
8	12	27	51.4	46	37	51.3	67[a]	33	4	0.51
9	14	02	30.3	46	40	50.6	- - -	80	3	0.53
10	14	36	21.5	46	33	21.6	- - -	- - -	2	0.55

[a] Some data obtained during poor conditions.

Fig. 1.—

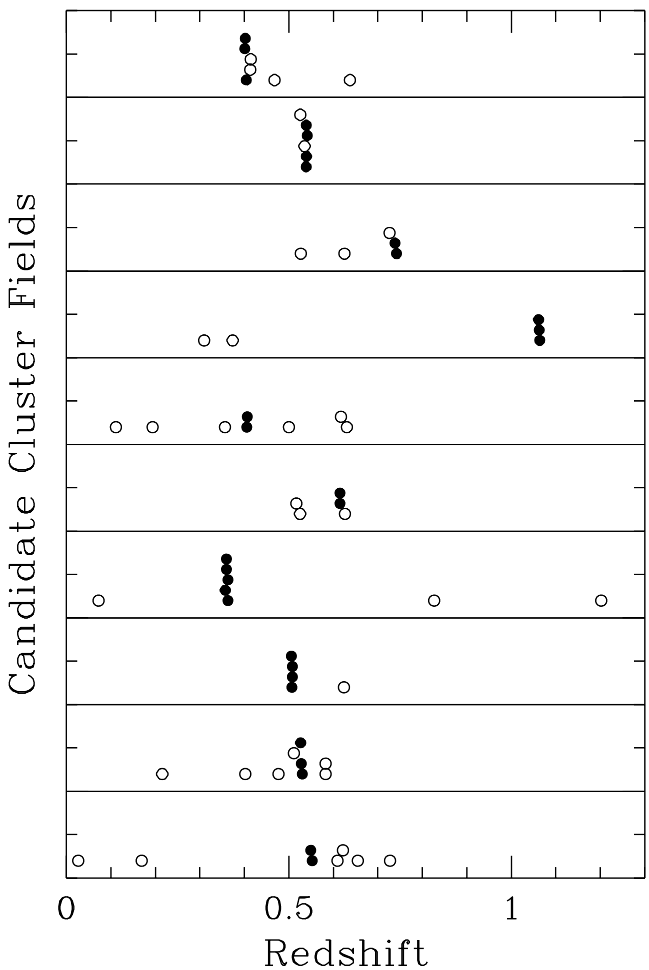

Fig. 2.—

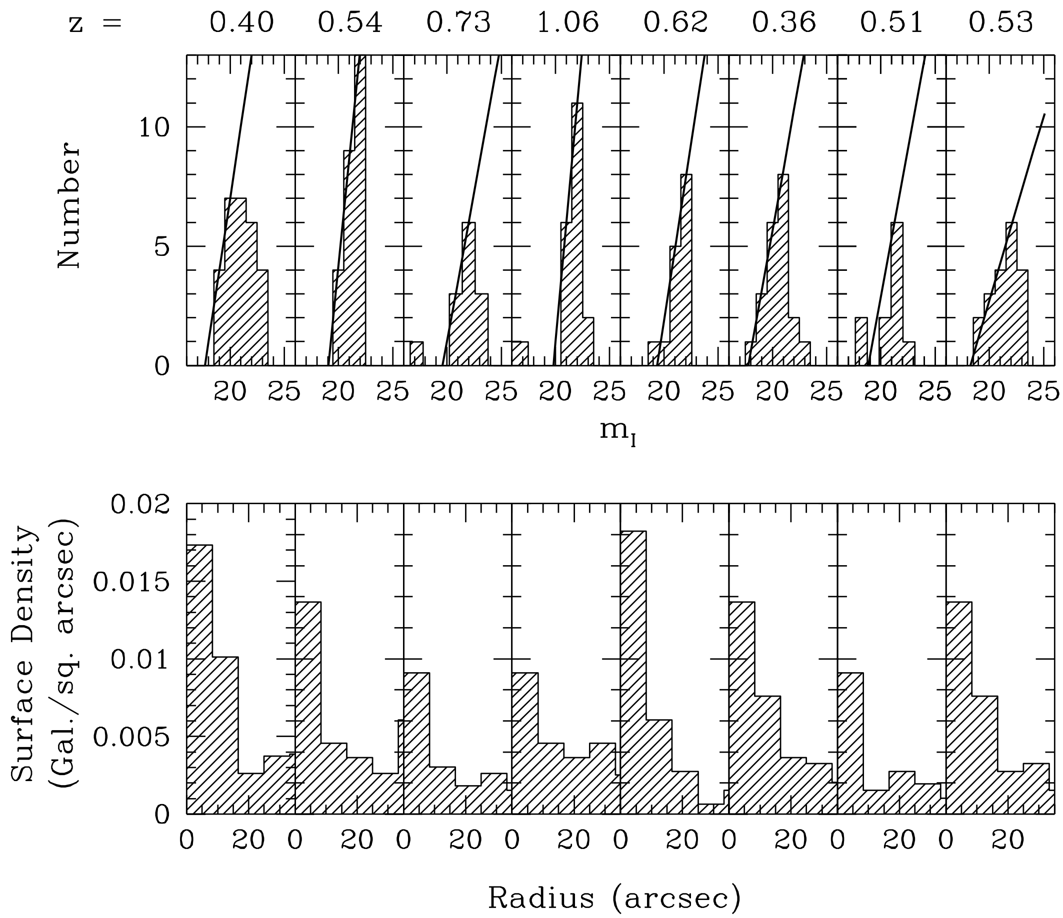
z =
0.40
0.54
0.73
1.06
0.62
0.36
0.51
0.53
Number
m$_I$
Surface Density
(Gal./sq. arcsec)
Radius (arcsec)

Fig. 3.—